

# Complete gauge-invariant formalism for arbitrary second-order perturbations of a Schwarzschild black hole

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Using recently developed efficient symbolic manipulations tools, we present a general gauge-invariant formalism to study arbitrary radiative ( $l \geq 2$ ) second-order perturbations of a Schwarzschild black hole. In particular, we construct the second-order Zerilli and Regge-Wheeler equations under the presence of any two first-order modes, reconstruct the perturbed metric in terms of the master scalars, and compute the radiated energy at null infinity. The results of this paper enable systematic studies of generic second-order perturbations of the Schwarzschild spacetime, in particular, studies of mode-mode coupling and nonlinear effects in gravitational radiation, the second-order stability of the Schwarzschild spacetime, or the geometry of the black hole horizon.

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## I. INTRODUCTION

Nonlinearities are a characteristic feature of general relativity. Classifying the possible types of nonlinearity can help us much in understanding and interpreting the results of observations or simulations of gravitational phenomena. For instance, the space-based gravitational-wave observatory LISA will be able to detect quasinormal mode coupling and frequency mixing in the ringdown phase of the collision of two supermassive black holes at distances of 1 Gpc [1]. Perturbation theory offers a systematic study of nonlinearities, at least for moderate couplings, and it is hence worth developing a complete formalism for perturbations in general relativity.

During the last three years, we have prepared a combination of ideas and tools on which such a systematic approach to metric perturbation theory in general relativity can be based. This includes, among other things, general explicit formulas for the perturbations of curvature tensors at any order [2], a general analysis of gauge-invariance [3], and the construction of specialized and efficient tensor computer algebra tools to handle the enormous equations of perturbative general relativity [4,5]. For definiteness, and because this is the most standard scenario in astrophysical applications, we have generally focused on spherical background spacetimes.

The purpose of this article is to apply that general formalism to a Schwarzschild background. Linear perturbations of Schwarzschild have been studied since the pioneering work of Regge and Wheeler [6], and later

Zerilli [7] and Moncrief [8], in which they were already able to identify and describe the two polarizations of gravitational waves, giving two decoupled wave equations for them.

The first studies of second-order black hole perturbations were carried out in the seventies [9,10] in order to study the nonlinear stability of the Schwarzschild solution. In the mid-nineties, motivated by the close-limit approximation [11], gauge-invariant second-order generalizations of the Regge-Wheeler and Zerilli-Moncrief formalisms were developed and applied to a variety of close limit-type initial data for binary black holes; see [12,13] and references therein. More recently, the relevance of second-order perturbation theory on an extreme mass-ratio inspiral has been evaluated [14]. In general, those references have focused on the study of the self-coupling of a particular first-order mode and how that generates some second-order mode.

We present here a complete, gauge-invariant Regge-Wheeler-Zerilli-Moncrief like formalism for *arbitrary*  $l \geq 2$  first- and second-order perturbations of a Schwarzschild black hole. In particular, we derive the general first- and second-order Regge-Wheeler and Zerilli master variables and the equations they obey. We also reconstruct the perturbed metric in terms of those scalars, as well as computing the radiated energy at null infinity.

Most of our results are not only gauge invariant but also covariant; that is, independent of the background coordinates. This is analogous to the covariant formalisms for

linear perturbation theory in Refs. [15–18]. This is a necessary step to, for example, test the geometry near the horizon or null infinity, for which Schwarzschild coordinates are inadequate. Other results are still given in Schwarzschild coordinates, for simplicity.

The organization of this paper is as follows: we start in Sec. II by reviewing the formalism of [2,3]. Section III presents the high-order Regge-Wheeler and Zerilli equations, and Sec. IV sketches how we compute the radiated energy. Setting up the arena for the second-order treatment, Sec. V rederives in a compact yet complete way a gauge-invariant version of the Regge-Wheeler-Zerilli first-order formalism. Finally, Sec. VI presents our general second-order Regge-Wheeler and Zerilli equations, their sources, and the computation of the radiated energy in terms of our second-order Regge-Wheeler and Zerilli functions.

We will use natural units in which  $G = c = 1$ .

## II. HIGH-ORDER GERLACH AND SENGUPTA FORMALISM

### A. Background spherical spacetime

This section briefly summarizes the formalism introduced in Refs. [2,3] to deal with high-order perturbations of a spherical spacetime. This formalism can be regarded as the generalization to higher orders of the Gerlach-Sengupta linear formalism [15,16].

We start by decomposing the spacetime manifold  $\mathcal{M}$  as a product  $\mathcal{M} \equiv \mathcal{M}^2 \times S^2$ , where  $\mathcal{M}^2$  is a two-dimensional Lorentzian manifold and  $S^2$  the two-sphere. We will use Greek letters ( $\mu, \nu, \dots$ ) for four-dimensional indices, capital Latin letters ( $A, B, \dots$ ) for indices on  $\mathcal{M}^2$ , and lowercase Latin letters ( $a, b, \dots$ ) for indices on the sphere. With this notation, and choosing an adapted coordinated system, a general spherically symmetric back-

ground metric with signature  $(-+++)$  is given by

$$g_{\mu\nu}(x^D, x^d)dx^\mu dx^\nu = g_{AB}(x^D)dx^A dx^B + r^2(x^D)\gamma_{ab}(x^d)dx^a dx^b, \quad (1)$$

where  $g_{AB}$  is a metric field and  $r$  a scalar field, both on the manifold  $\mathcal{M}^2$ , and  $\gamma_{ab}$  is the unit metric on the sphere  $S^2$ . The respective coordinate systems on the two-dimensional manifolds can still be freely specified.

We define the following notation for the covariant derivatives associated with each metric:

$$g_{AB|C} = 0, \quad \gamma_{ab;c} = 0. \quad (2)$$

For future reference, we define the vector  $v_A \equiv r_{|A}/r$ .

### B. Nonlinear perturbations

In perturbation theory one works with a family of spacetimes  $\{\mathcal{M}(\varepsilon), \tilde{g}(\varepsilon)\}$  depending on a dimensionless parameter  $\varepsilon$ . The background spacetime is the member of this family for which  $\varepsilon = 0$ , and it is assumed to be a known solution of the Einstein equations. Performing a Taylor expansion around the background metric  $g_{\mu\nu}$ ,

$$\tilde{g}_{\mu\nu}(\varepsilon) = g_{\mu\nu} + \sum_{n=1}^{\infty} \frac{\varepsilon^n}{n!} \{n\}h_{\mu\nu}, \quad (3)$$

defines the perturbations  $\{n\}h_{\mu\nu}$ , which are tensors on the background manifold. In practice, we will always work at a given finite maximum order  $N$ , truncating the series at that order.

Using the basis of tensor harmonics described in Appendix A, we decompose the perturbations of the metric in the following way:

$$\{n\}h_{\mu\nu} \equiv \sum_{l,m} \left( \begin{aligned} &\{n\}H_{l\ AB}^m Z_l^m \\ &+ \{n\}H_{l\ B}^m Z_{l\ a}^m + \{n\}h_{l\ B}^m X_{l\ a}^m \\ &+ \{n\}K_l^m r^2 \gamma_{ab} Z_l^m + \{n\}G_l^m r^2 Z_{l\ ab}^m + \{n\}h_l^m X_{l\ ab}^m \end{aligned} \right), \quad (4)$$

where  $l$  runs over all non-negative integers and  $m$  is limited to the range  $-l \leq m \leq l$ .

Perturbations of all relevant curvature tensors in terms of metric perturbations have been given in [2], in particular, those of the Einstein tensor. The latter have also been decomposed there in spherical harmonics at second order, giving full equations of motion for the harmonic coefficients of the metric.

Now we proceed to extract the gauge freedom present in the previous decomposition (4). Per each perturbative order  $n$ , four of those ten components are free.

The most natural gauge choice in spherical symmetry is the one introduced by Regge and Wheeler (RW) [6] for linear perturbations. Here, we use those same conditions at all orders, for  $l \geq 2$

$$\{n\}H_{l\ A}^m = 0, \quad \{n\}G_l^m = 0, \quad \{n\}h_l^m = 0. \quad (5)$$

Alternatively, it is possible to construct explicit gauge-invariant combinations of those harmonic coefficients, as explained in [3]. The idea is simply to select a gauge and define the gauge invariants to be the expression of the general gauge transformation of the metric functions from an arbitrary gauge to that selected gauge. Around spherical symmetry, the requirement that the gauge invariants are local (almost) uniquely selects the RW gauge as the preferred reference gauge, and this is what we will use.

Schematically (see [3] for more details) the gauge invariants associated with the RW gauge are given by

$$\begin{aligned} \{n\}\mathcal{K}_l^m{}_{AB} &= \{n\}H_l^m{}_{AB} + \left(\frac{r^2}{2}\{n\}G_l^m{}_{|A} - \{n\}H_l^m{}_{|A}\right)_{|B} \\ &+ \left(\frac{r^2}{2}\{n\}G_l^m{}_{|B} - \{n\}H_l^m{}_{|B}\right)_{|A} + \{n\}R_l^m{}_{AB}, \end{aligned} \quad (6)$$

$$\begin{aligned} \{n\}\mathcal{K}_l^m &= \{n\}K_l^m + 2v^A \left(\frac{r^2}{2}\{n\}G_l^m{}_{|A} - \{n\}H_l^m{}_{|A}\right) \\ &+ \frac{l(l+1)}{2}\{n\}G_l^m + \{n\}R_l^m, \end{aligned} \quad (7)$$

$$\{n\}\kappa_l^m{}_A = \{n\}h_l^m{}_A - \frac{r^2}{2}\left(\frac{\{n\}h_l^m}{r^2}\right)_{|A} + \{n\}R_l^m{}_A, \quad (8)$$

where the terms  $\{n\}R_l^m{}_{AB}$ ,  $\{n\}R_l^m{}_A$  and  $\{n\}R_l^m$  are polynomial combinations of the lower-order harmonic coefficients

$$\{\{k\}H_l^m{}_A, \{k\}G_l^m, \{k\}h_l^m\}, \quad \text{with } k < n, \quad (9)$$

all vanishing in RW gauge, by construction. These  $R$  terms can be easily written in terms of the  $\mathcal{H}$  objects introduced in Ref. [3]. Because of the  $k < n$  condition, those terms are not present in linearized perturbations ( $n = 1$ ). For second-order perturbations ( $n = 2$ ), they are quadratic in the first-order quantities  $\{\{1\}H_l^m{}_A, \{1\}G_l^m, \{1\}h_l^m\}$ , and so forth for higher  $n$ .

Once more, the values of  $\{n\}\mathcal{K}_l^m{}_{AB}$ ,  $\{n\}\mathcal{K}_l^m$ ,  $\{n\}\kappa_l^m{}_A$  in any gauge coincide with their values in the RW gauge since all except the leading terms in Eqs. (6)–(8) vanish in this gauge. Because of this we can do calculations in the RW gauge, yet still recover the form of any expression in a generic gauge by making use of the definitions (6)–(8). We will take advantage of this fact later.

### III. HIGH-ORDER REGGE-WHEELER AND ZERILLI EQUATIONS

From now on we shall assume that our background solution is the Schwarzschild spacetime. The perturbative formalism summarized in the previous section allows us to work with arbitrary coordinates on the reduced manifold  $\mathcal{M}^2$ . However, we will sometimes use Schwarzschild coordinates  $(t, r)$  as intermediate tools for computing expressions, which in the end will be valid in any asymptotically flat background coordinates. Then we will use the following shorthands for coordinate derivatives acting on any object  $\omega$ :

$$\dot{\omega} \equiv \frac{\partial \omega}{\partial t}, \quad \omega' \equiv \frac{\partial \omega}{\partial r}. \quad (10)$$

When studying perturbations of the Schwarzschild spacetime, it is possible to reduce the perturbed Einstein equations to two wave equations for two *master* functions, one of odd/axial parity and another one even/polar parity, and this is true at all perturbative orders. These two functions fully describe the gravitational content of the system,

and actually the whole metric perturbation at order  $n$  can be reconstructed from the master variables at orders  $k \leq n$ .

To alleviate the notation, from now on we will drop the  $(l, m)$  labels of the harmonic coefficients, with only a few exceptions like the formulas for the radiated power.

#### A. The even/polar parity sector

We define the  $n$ th order Zerilli function as the following combination of polar harmonic coefficients:

$$\{n\}\Psi \equiv \frac{r^4}{3M + \lambda r} (v^B \{n\}\mathcal{K}_{AB} - \{n\}\mathcal{K}_{|A})v^A + r \{n\}\mathcal{K}, \quad (11)$$

where  $\lambda \equiv (l-1)(l+2)/2$ . This variable is given in terms of the  $n$ th order gauge invariants tied to the Regge-Wheeler gauge. To recover the form of the Zerilli function in a different gauge, we just need to replace the invariants by their explicit form in terms of a generic gauge (6)–(8). Then, the Zerilli variable takes the following form in Schwarzschild coordinates:

$$\begin{aligned} \{n\}\Psi &\equiv \frac{(2M-r)}{3M + \lambda r} [(2M-r) \{n\}H_{rr} + r^2 \{n\}K'] + r \{n\}K \\ &+ \frac{l(l+1)}{3M + \lambda r} (2M-r) \{n\}H_r + \frac{1}{2} l(l+1) r \{n\}G \\ &+ \{n\}Q_\Psi, \end{aligned} \quad (12)$$

where the subindices  $t$  and  $r$  stand for components of the different tensors in these coordinates. In the previous expression  $\{n\}Q_\Psi$  collects the terms  $\{\{n\}R_{AB}, \{n\}R_A, \{n\}R\}$ , and hence it is itself a polynomial in the lower-order variables (9). Notice that in Eq. (12) the last three terms, including  $\{n\}Q_\Psi$ , are zero when imposing the RW gauge.

The Zerilli master function satisfies the following wave equation:

$$\{n\}\Psi^{lA}{}_A - V_Z \{n\}\Psi = \{n\}\mathcal{S}_\Psi. \quad (13)$$

The source term  $\{n\}\mathcal{S}_\Psi$  depends on the lower-order perturbations, while the potential is

$$V_Z \equiv \frac{l(l+1)}{r^2} - \frac{6M}{r^3} \frac{r^2 \lambda (\lambda + 2) + 3M(r-M)}{(r\lambda + 3M)^2}. \quad (14)$$

In particular, when using the tortoise coordinates  $(t, r^*)$  [with  $r^* = r + 2M \ln(r/(2M) - 1)$ ] the differential operator takes the following simple form:

$$\{n\}\Psi^{lA}{}_A \equiv \left(1 - \frac{2M}{r}\right)^{-1} \left(-\frac{\partial^2 \{n\}\Psi}{\partial t^2} + \frac{\partial^2 \{n\}\Psi}{\partial r^{*2}}\right). \quad (15)$$

In order to obtain the Zerilli Eq. (13) one just take some linear combination of the equations of motion for different polar harmonic coefficients. Taking the very same combinations of their corresponding sources, the source  $\{n\}\mathcal{S}_\Psi$  is constructed. Obviously, the first-order source  $\{1\}\mathcal{S}_\Psi$  is zero. The second-order one can be given as

$$\begin{aligned}
{}^{(2)}\mathcal{S}_\Psi \equiv & \sum_{\hat{l}, \hat{l}} \sum_{\hat{m}, \hat{m}} \frac{l(l+1)}{r} {}^{(\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m} + \frac{r^4}{3M + \lambda r} v^A \left[ {}^{(\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m B}{}_{B|A} - {}^{(\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m}{}_{AB}{}^{|B} - \frac{l(l+1)}{r^2} {}^{(\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m}{}_A \right] \\
& - \frac{r}{4(3M + \lambda r)^2} \left[ (84M^2 + 12(l^2 + l - 5)Mr + 2\lambda(l^2 + l - 4)r^2) {}^{(\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m}{}_A^A \right. \\
& \left. + 4r^3(12M + 2\lambda r)v^A v^B {}^{(\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m}{}_{AB} \right], \tag{16}
\end{aligned}$$

where  $(\hat{l}, \hat{m})$  and  $(\bar{l}, \bar{m})$  are a pair of two first-order modes, which contribute to the second-order  $(l, m)$  mode. The sources  $S$  in the previous expression are explicitly given in Ref. [2]. The polarity sign  $\epsilon$  is defined as  $\epsilon \equiv (-1)^{(\hat{l} + \bar{l} - l)}$ .

Note finally that the definition of the high-order Zerilli function (11) is essentially determined up to addition of low-order gauge-invariant terms. That is, the addition of such low-order terms would keep the same form of the Zerilli Eq. (13), in particular, with the same potential  $V_Z$ , but would change the source  ${}^{(n)}S_\Psi$ . The definition given in (11) is just the simplest possibility, and follows [19]. We will later make use of this freedom.

This article assumes a vacuum spacetime, both at the background and perturbed levels. Including matter and its perturbations would introduce additional source terms in the master equations of motion, as well as additional evolution equations for the variables describing the matter fields. Reference [2] gives the equations obtained by second-order perturbation of energy-momentum conservation, and Ref. [3] shows how to describe the new matter fields using gauge-invariant variables.

### B. Odd/axial parity sector

The Gerlach and Sengupta (GS) master scalar is defined as the antisymmetrized derivative of the axial invariant vector  $\kappa_A/r^2$ ,

$${}^{(n)}\Pi \equiv \epsilon^{AB} \left( \frac{{}^{(n)}\kappa_A}{r^2} \right)_{|B}. \tag{17}$$

Like the Zerilli function, it is given in terms of some of the RW gauge-invariants (6)–(8). In a generic gauge it takes the form

$${}^{(n)}\Pi = \epsilon^{AB} \left( \frac{{}^{(n)}h_A}{r^2} \right)_{|B} + {}^{(n)}Q_\Pi, \tag{18}$$

where  ${}^{(n)}Q_\Pi$  is a source term that depends on lower-order perturbations, and which is zero in the RW gauge.

It obeys the GS master equation

$$- \left[ \frac{1}{2r^2} (r^4 {}^{(n)}\Pi)_{|A} \right]_{|A} + \frac{(l-1)(l+2)}{2} {}^{(n)}\Pi = {}^{(n)}S_\Pi. \tag{19}$$

The second-order source can be written in terms of the source of the Einstein equations

$${}^{(2)}\mathcal{S}_\Pi = i\epsilon^{AB} \sum_{\hat{l}, \hat{l}} \sum_{\hat{m}, \hat{m}} {}^{(-\epsilon)}S_{\hat{l} \hat{l} \hat{l}}^{\hat{m} \hat{m} m}{}_{A|B}. \tag{20}$$

As in the even-parity case, the sources  $S$  that appear in the previous expression are explicitly given in Ref. [2]. Equation (19) is a wave equation for the scalar  ${}^{(n)}\Pi$ . It contains all the relevant physical information of the axial sector. As we will see, all metric components can be algebraically reconstructed from this scalar.

We will use the above definition for  ${}^{(n)}\Pi$  for historical reasons. But, in fact, a better choice [20] is the rescaled  ${}^{(n)}\tilde{\Pi} \equiv r^3 {}^{(n)}\Pi$ , because its evolution equation has no first-order derivatives,

$${}^{(n)}\tilde{\Pi}_{|A}{}^A - V_{RW} {}^{(n)}\tilde{\Pi} = -2r {}^{(n)}S_\Pi. \tag{21}$$

This equation is valid in any spherically symmetric background and the potential is given by

$$V_{RW} = \frac{l(l+1)}{r^2} - \frac{3}{r^2} (1 - g^{AB} r_{|A} r_{|B}). \tag{22}$$

For the Schwarzschild spacetime it is

$$V_{RW} = \frac{l(l+1)}{r^2} - \frac{6M}{r^3}, \tag{23}$$

and Eq. (21) becomes the standard RW equation.

One of the main advantages of the GS master scalar is that the perturbation of the metric can be *algebraically* reconstructed. But there are some other variables that obey the same RW equation. In particular, one that will be very useful for our purposes is the one introduced by Regge and Wheeler themselves in their seminal paper [6]. Its gauge-invariant generalization to higher orders takes the following form:

$${}^{(n)}\Phi \equiv v^A {}^{(n)}\kappa_A. \tag{24}$$

When using Schwarzschild coordinates for the background this definition becomes

$${}^{(n)}\Phi = \frac{2M - r}{2r^2} \left[ {}^{(n)}h' - 2 {}^{(n)}h_r - \frac{2}{r} {}^{(n)}h \right] + {}^{(n)}Q_\Phi, \tag{25}$$

where  ${}^{(n)}Q_\Phi$  is the standard term that depends on lower-order perturbations and vanishes when particularizing to the RW gauge. There are practical advantages and disadvantages for each of these definitions for the master scalar in the odd-parity sector, as we will see in Sec. VB.



At linear order,  $\{^1\}\Phi$  obeys the same equation as  $\{^1\}\tilde{\Pi}$ . But at second order the source term changes,

$$\{^2\}\Phi_{|A} - V_{\text{RW}}\{^2\}\Phi = \{^2\}\mathcal{S}_\Phi, \quad (26)$$

with

$$\begin{aligned} \{^2\}\mathcal{S}_\Phi \equiv & \sum_{\hat{l}, \bar{l}} \sum_{\hat{m}, \bar{m}} \frac{2i}{r^3} (3M - r)^{(-e)} S_{\hat{l} \bar{l}}^{\hat{m} \bar{m}} \\ & + iv^A \left[ S_{\hat{l} \bar{l}}^{\hat{m} \bar{m}} - 2^{(-e)} S_{\hat{l} \bar{l}}^{\hat{m} \bar{m}} \right]_{|A}. \end{aligned} \quad (27)$$

#### IV. RADIATED POWER

To compute the power radiated to infinity by gravitational waves we will use the Landau and Lifshitz (LL) formula [21,22]

$$\begin{aligned} \frac{d\text{Power}}{d\Omega} = & \frac{1}{16\pi r^2} \left\{ \frac{1}{\sin^2\theta} \left| \frac{\partial \tilde{g}_{\theta\phi}}{\partial t} \right|^2 \right. \\ & \left. + \frac{1}{4} \left| \frac{\partial \tilde{g}_{\theta\theta}}{\partial t} - \frac{1}{\sin^2\theta} \frac{\partial \tilde{g}_{\phi\phi}}{\partial t} \right|^2 \right\}. \end{aligned} \quad (28)$$

This expression is only valid in an asymptotically flat (AF) gauge, by which we mean, following [22],

$$\{^n\}h_{tt}, \{^n\}h_{rr}, \{^n\}h_{tr} = O(r^{-2}), \quad (29)$$

$$\{^n\}h_{t\theta}, \{^n\}h_{t\phi}, \{^n\}h_{r\theta}, \{^n\}h_{r\phi} = O(r^{-1}), \quad (30)$$

$$\{^n\}h_{\theta\theta}, \{^n\}h_{\phi\phi}, \{^n\}h_{\theta\phi} = O(r), \quad (31)$$

$$\gamma^{ab}\{^n\}h_{ab} = O(r^0) \quad (32)$$

to the desired order  $n$ .

Once the Regge-Wheeler and Zerilli functions are known up to a given order, one can reconstruct the perturbed metric components in an AF gauge (we will turn to

this below). Once those are known, we could in principle use Eq. (28) to compute the radiated energy.

It turns out that the RW gauge is not asymptotically flat. Because of that we will need to (explicitly or implicitly, this will be discussed later) make a gauge transformation from the RW gauge to an asymptotically flat one. Once in that gauge, we will apply Eq. (28) in order to obtain the radiated power.

It is useful to rewrite the Landau and Lifshitz formula (28) in a covariant way with respect to the coordinates on  $S^2$ , as follows: We first introduce the trace-free projector to the sphere (recall that  $\gamma_{ab}$  is the standard, unit metric on the sphere),

$$P_{ab}{}^{cd} \equiv \gamma_a{}^c \gamma_b{}^d - \frac{1}{2} \gamma_{ab} \gamma^{cd}, \quad (33)$$

such that for any rank-two tensor  $A_{cd}$  we have that  $P_{ab}{}^{cd} A_{cd}$  is trace free. It allows us to introduce the projected trace-free metric on the sphere

$$i_{ab} \equiv P_{ab}{}^{cd} \tilde{g}_{cd}, \quad (34)$$

so that formula (28) can be rewritten in the following way:

$$\frac{d\text{Power}}{d\Omega} = \frac{1}{32\pi r^2} \left( \frac{\partial i_{ab}}{\partial t} \right) \gamma^{ac} \gamma^{bd} \left( \frac{\partial i_{cd}}{\partial t} \right)^*, \quad (35)$$

where the star denotes complex conjugation.

Using the perturbative expansion in spherical harmonics (4), the projected trace-free metric takes the form

$$i_{ab} = \sum_{n=1}^{\infty} \frac{\varepsilon^n}{n!} \sum_{l,m} \{r^2\}^{(n)} G_l^{m\text{AF}} Z_{ab}^m + \{^n\}h_l^{m\text{AF}} X_{ab}^m, \quad (36)$$

where the superscript AF stands for any asymptotically flat gauge. Note that the harmonic labels  $l=0, 1$  do not contribute to the last sum since the coefficients  $G_l^m$  and  $h_l^m$  vanish for these cases.

Finally, making use of the normalization shown in Appendix A and the fact that the tensor spherical harmonics are trace free, it is easy to integrate the emitted power over the solid angle to get

$$\text{Power} = \frac{1}{64\pi r^2} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} \frac{\varepsilon^{j+k}}{j!k!} \sum_{l,m} \frac{(l+2)!}{(l-2)!} \left\{ r^4 \left( \frac{\partial^{[j]} G_l^{m\text{AF}}}{\partial t} \right) \left( \frac{\partial^{[k]} G_l^{m\text{AF}}}{\partial t} \right)^* + \left( \frac{\partial^{[j]} h_l^{m\text{AF}}}{\partial t} \right) \left( \frac{\partial^{[k]} h_l^{m\text{AF}}}{\partial t} \right)^* \right\}. \quad (37)$$

Therefore, the problem of extracting the radiated power with an order of  $\varepsilon^n$  reduces to finding the value of the time derivative of the harmonic coefficients  $\{^k\}G_l^m$  and  $\{^k\}h_l^m$ , for all  $k < n$ , in an asymptotically flat gauge. Note that in the last formula there is no coupling between modes with different harmonic labels. This is so because of the integrated character of the total emitted power, and the orthogonality between different spherical harmonics. This has important consequences when one wants to obtain

the radiated power up to a given order  $\varepsilon^n$  consistently, as discussed later.

#### V. FIRST-ORDER PERTURBATIONS

We now turn our attention to the reconstruction of the metric components from the *first-order* master functions, and the computation of the radiated energy in terms of them. The reason for rederiving these results here is two-fold. First, to fix the conventions that we will use in the

second-order case, in which the first-order perturbations will appear as “source terms.” Second, to sketch in a less complicated case the type of calculations presented in the next section for second-order perturbations.

After writing down the first-order master equations we reconstruct the metric in the RW gauge. One can explicitly transform the result from the latter to an arbitrary gauge. In fact, in order to use the Landau and Lifshitz formula (28) we must use an asymptotically flat gauge. As we will see, the RW gauge is not asymptotically flat. Because of this, following [12], we will first perform an explicit asymptotic gauge transformation from the RW gauge to an AF one and afterwards apply the LL formula.

In addition, following [19], we use an alternative way of computing the radiated energy, which exploits the gauge-invariant form of the master functions presented in the previous section, instead of making an explicit asymptotic gauge transformation.

In this section we will remove all harmonic labels, as well as the  $n = 1$  labels, since all objects will be of first order and correspond to a generic harmonic pair  $(l, m)$ .

### A. Even-parity/polar sector

At first order, the Zerilli equation is a wave equation without sources,

$$\Psi^{|A}{}_{;A} - V_Z \Psi = 0. \quad (38)$$

This master variable contains the physical information of the system since it is possible to reconstruct from it all components of the perturbation of the metric, in the RW gauge. Making use of its definition (12) and the equations of motion for different harmonic coefficients, we obtain the following reconstruction in Schwarzschild coordinates:

$$\begin{aligned} H_{tt} = & \frac{2M - r}{4l(l+1)r^3(3M + \lambda r)^2} \\ & \times \{2(2M - r)r^2(6M + 2\lambda r)^2\Psi'' \\ & + 4r[\lambda(l^2 + l - 8)r^2M - 2\lambda^2r^3 - 18M^3]\Psi' \\ & + 4[18M^3 + 18\lambda rM^2 + 6\lambda^2r^2M + l(l+1)\lambda^2r^3]\Psi\}, \end{aligned} \quad (39)$$

$$H_{rr} = \frac{r^2}{(2M - r)^2} H_{tt}, \quad (40)$$

$$\begin{aligned} H_{tr} = & \frac{2(3M^2 + 3\lambda rM - \lambda r^2)}{l(l+1)[6M^2 + (l^2 + l - 5)rM - \lambda r^2]} \dot{\Psi} \\ & + \frac{2r}{l(l+1)} \dot{\Psi}', \end{aligned} \quad (41)$$

$$\begin{aligned} K = & \frac{1}{2l(l+1)r^2(3M + \lambda r)} \\ & \times \{2r[-12M^2 - 2(l^2 + l - 5)rM + 2\lambda r^2]\Psi' \\ & + [24M^2 + 12\lambda rM + (l-1)l(l+1)(l+2)r^2]\Psi\}. \end{aligned} \quad (42)$$

Introducing these relations into the linearized Einstein equations, one can show that all of them are trivially satisfied if the Zerilli Eq. (38) holds.

Next we explicitly display the divergent nature of these quantities (and, as a consequence, of the first-order metric perturbations in the RW gauge). For that purpose we temporarily introduce Schwarzschild coordinates  $(t, r)$  and the tortoise one  $r^*$ . The Zerilli function  $\Psi$  can be expanded in inverse powers of  $r$ , with coefficients depending on the retarded time  $u \equiv t - r^*$ ,

$$\Psi \equiv \Psi_0(u) + \frac{\Psi_1(u)}{r} + \frac{\Psi_2(u)}{r^2} + \mathcal{O}\left(\frac{1}{r^3}\right). \quad (43)$$

The Zerilli equation is then equivalent to a series of relations, order by order in  $r$ , among those coefficients:

$$\begin{aligned} \Psi_0(u) = & \frac{2}{l(l+1)} \ddot{F}(u), & \Psi_1(u) = & \dot{F}(u), \\ \Psi_2(u) = & \frac{\lambda}{2} F(u) - \frac{3M(\lambda+2)}{2\lambda(\lambda+1)} \dot{F}(u), \end{aligned} \quad (44)$$

where  $\dot{F}(u) = dF(u)/du$ . The function  $F(u)$  can be understood as the free data at null infinity.

In order to see the divergent behavior of the harmonic coefficients in RW gauge at null infinity, we replace the expansion (43) in (39)–(42) to obtain

$$H_{tt} = \frac{4\ddot{F}}{l^2(l+1)^2} r + \frac{4\lambda\ddot{F}}{l^2(l+1)^2} + \mathcal{O}\left(\frac{1}{r}\right), \quad (45)$$

$$H_{rr} = \frac{4\ddot{F}}{l^2(l+1)^2} r + \frac{16M\ddot{F} + 4\lambda\ddot{F}}{l^2(l+1)^2} + \mathcal{O}\left(\frac{1}{r}\right), \quad (46)$$

$$H_{tr} = -\frac{4\ddot{F}}{l^2(l+1)^2} r - \frac{8M\ddot{F} + 4\lambda\ddot{F}}{l^2(l+1)^2} + \mathcal{O}\left(\frac{1}{r}\right), \quad (47)$$

$$K = -\frac{4\ddot{F}}{l^2(l+1)^2} r + \mathcal{O}\left(\frac{1}{r^2}\right), \quad (48)$$

where the orders  $r^0$  and  $r^{-1}$  vanish for the harmonic coefficient  $K$ .

In order to apply the LL formula we perform an explicit asymptotic (that is, near null infinity) transformation from the RW gauge to an AF one. We will not show the form of the resulting change of coordinates but instead directly show the asymptotic form of the metric coefficients in the new gauge

$$H_{tt}^{\text{AF}} = 0 + \mathcal{O}\left(\frac{1}{r^3}\right), \quad (49)$$

$$H_{rr}^{\text{AF}} = 0 + \mathcal{O}\left(\frac{1}{r^3}\right), \quad (50)$$

$$H_{tr}^{\text{AF}} = 0 + \mathcal{O}\left(\frac{1}{r^3}\right), \quad (51)$$

$$H_t^{\text{AF}} = \left\{ \dot{\Phi}_1 - \frac{1}{4l^2(l+1)^2} \left[ 4M\ddot{F} + \frac{(l+2)!}{(l-2)!} \dot{F} \right] \right\} \frac{1}{r} + \mathcal{O}\left(\frac{1}{r^2}\right), \quad (52)$$

$$H_r^{\text{AF}} = -\left\{ \dot{\Phi}_1 - \frac{1}{2l^2(l+1)^2} [2M\ddot{F} + \lambda(l^2 + l - 8)\dot{F}] \right\} \frac{1}{r} + \mathcal{O}\left(\frac{1}{r^2}\right), \quad (53)$$

$$G^{\text{AF}} = \frac{4\ddot{F}}{l^2(l+1)^2} \frac{1}{r} + \frac{4\lambda\dot{F}}{l^2(l+1)^2} \frac{1}{r^2} + 2\Phi_1 \frac{1}{r^3} + \mathcal{O}\left(\frac{1}{r^4}\right), \quad (54)$$

$$K^{\text{AF}} = 0 + \mathcal{O}\left(\frac{1}{r^3}\right), \quad (55)$$

where zeros stand to show that in fact one could ask for faster decay rates than the ones defined in (29)–(32) and  $\Phi_1 = \Phi_1(u)$  is a gauge freedom that it is not fixed by the requirement of asymptotic flatness. From the behavior of the harmonic coefficient  $G$  in an asymptotically flat gauge (54) and the asymptotic expansion of the Zerilli function (43), it is easy to obtain

$$G^{\text{AF}} = \frac{2\Psi}{l(l+1)r} + \mathcal{O}\left(\frac{1}{r^2}\right). \quad (56)$$

Alternatively, this last relation can be directly obtained from the gauge-invariant definition of the Zerilli variable (11) and (12). Since that definition is valid for any gauge we can suppose that we are in an AF gauge. Imposing the decay rates (29)–(32) it is straightforward to obtain (56). The advantage of this last method is that we do not have to do an explicit asymptotic gauge transformation. The disadvantage is, however, that we need to assume that (29)–(32) is indeed possible.

Either way, using the relation (56) and the LL formula we obtain the radiated power in terms of the Zerilli function,

$$[\text{Power}]^{\text{polar}} = \frac{\varepsilon^2}{16\pi} \sum_{l,m} \frac{(l-1)(l+2)}{l(l+1)} \left| \frac{\partial \Psi_l^m}{\partial t} \right|^2. \quad (57)$$

Since this expression holds asymptotically, we can now forget that we have used intermediate Schwarzschild-type

coordinates to derive it, since it will hold for any time coordinate that agrees with it at infinity.

## B. Odd-parity/axial sector

We proceed as in the even-parity/polar sector. Making use of the evolution equation for the gauge-invariant vector  $\kappa_A$ , we reconstruct the metric from the RW scalar  $\Pi$  satisfying the RW equation

$$-\left[ \frac{1}{2r^2} (r^4 \Pi)^{|A} \right]_{|A} + \frac{(l-1)(l+2)}{2} \Pi = 0, \quad (58)$$

in the RW gauge:

$$h_t = \frac{r^2}{2\lambda} (2M - r)(4\Pi + r\Pi'), \quad (59)$$

$$h_r = \frac{r^5}{2\lambda(2M - r)} \ddot{\Pi}. \quad (60)$$

Next we expand the master scalar in inverse powers of  $r$  near asymptotic null infinity ( $r \rightarrow \infty$ ,  $u = \text{const}$ ). Since  $\tilde{\Pi} = r^3 \Pi$  obeys a standard wave equation, our master scalar will have the following behavior:

$$\Pi \equiv \frac{\Pi_0(u)}{r^3} + \frac{\Pi_1(u)}{r^4} + \frac{\Pi_2(u)}{r^5} + \mathcal{O}\left(\frac{1}{r^6}\right). \quad (61)$$

We can define a function  $J(u)$  such that

$$\begin{aligned} \Pi_0(u) &= \frac{2}{l(l+1)} \ddot{J}(u), & \Pi_1(u) &= \dot{J}(u), \\ \Pi_2(u) &= \frac{\lambda}{2} J(u) - \frac{3M}{l(l+1)} \dot{J}(u). \end{aligned} \quad (62)$$

With these expansions at hand, we can obtain the precise divergent behavior of the RW gauge in terms of the function  $J(u)$ ,

$$h_t = \frac{r}{\lambda l(l+1)} \ddot{J} + \frac{1}{l(l+1)} \dot{J} + \mathcal{O}\left(\frac{1}{r}\right), \quad (63)$$

$$h_r = -\frac{r}{\lambda l(l+1)} \ddot{J} - \frac{2M}{\lambda l(l+1)} \ddot{J} - \frac{1}{2\lambda} \dot{J} + \mathcal{O}\left(\frac{1}{r}\right). \quad (64)$$

As in the even-parity/polar sector, we make an explicit asymptotic gauge transformation to an AF gauge. And, as in that sector, we do not show the details of the resulting transformation but instead the final asymptotic behavior of the metric in the new gauge:

$$h_t^{\text{AF}} = \left\{ \dot{\Xi}_0 + \frac{1}{4} \dot{J} + \frac{(l-2)!}{(l+2)!} M \ddot{J} \right\} \frac{1}{r} + \mathcal{O}\left(\frac{1}{r^2}\right), \quad (65)$$

$$h_r^{AF} = -\left\{\ddot{\Xi}_0 + \frac{(l-2)!}{(l+2)!}\left[M\ddot{J} + \frac{\lambda}{2}(l^2 + l - 8)\dot{J}\right]\right\}\frac{1}{r} + \mathcal{O}\left(\frac{1}{r^2}\right), \quad (66)$$

$$h^{AF} = -\frac{2r}{\lambda l(l+1)}\ddot{J} - \frac{2}{l(l+1)}\dot{J} + \frac{2}{r}\ddot{\Xi}_0 + \mathcal{O}\left(\frac{1}{r^2}\right), \quad (67)$$

where  $\ddot{\Xi}_0 = \ddot{\Xi}_0(u)$  is a residual gauge freedom. From there it is easy to obtain that asymptotically

$$h^{AF} = -\frac{r^4}{\lambda}\Pi + \mathcal{O}(r^0). \quad (68)$$

Replacing this result in the LL formula for the emitted power we obtain

$$[\text{Power}]^{\text{axial}} = \frac{\varepsilon^2 r^6}{16\pi} \sum_{l,m} \frac{l(l+1)}{(l-1)(l+2)} \left| \frac{\partial \Pi_l^m}{\partial t} \right|^2. \quad (69)$$

One can try to obtain relation (68) with a gauge-invariant approach, as we have done in the polar case. It is not possible in this sector, however, since the gauge-invariant form of the master variable  $\Pi$  (18) does not contain the harmonic coefficient  $h$ . Hence, if using that variable one has to go through the explicit gauge transformation. But at this point we note that there is another master variable  $\Phi$  whose gauge-invariant form (25) does contain the harmonic coefficient  $h$ . Making a transformation to outgoing coordinates and assuming that we are in an AF gauge we can easily obtain the relationship between  $\Phi$  and  $h$  at null infinity,

$$\dot{h}^{AF} = 2r\Phi + \mathcal{O}(r^0). \quad (70)$$

Therefore, the emitted power can also be given in terms of this last variable,

$$[\text{Power}]^{\text{axial}} = \frac{\varepsilon^2}{16\pi} \sum_{l,m} \frac{(l+2)!}{(l-2)!} |\Phi_l^m|^2. \quad (71)$$

Because we can apply this gauge-invariant approach to relate the master variable with the harmonic coefficient  $h$  at null infinity, at second-order we will use the variable  ${}^{(2)}\Phi$ . But there is one disadvantage of using  $\Phi$  instead of  $\Pi$ . We have shown above the reconstruction of the perturbations of the metric in the RW gauge in terms of  $\Pi$  (59). These relations are algebraic. If we try to do the same with the variable  $\Phi$ , we find that the reconstruction of the metric is not algebraic, but differential.

$$h_r = \frac{r^2}{(r-2M)}\Phi, \quad (72)$$

$$\dot{h}_t = \left(1 - \frac{2M}{r}\right)^2 \left(h_r' + \frac{2M}{r-2M} \frac{h_r}{r}\right). \quad (73)$$

The first expression is obtained from the very definition of the master variable  $\Phi$  (25), whereas the second one is the evolution equation for the component  $h_t$ . This is why we will use  $\Pi$  at linear order and  $\Phi$  at second.

## VI. SECOND-ORDER PERTURBATIONS

In order to solve for the second-order perturbations it is *in principle* enough to solve the Zerilli (13) and RW (26) equations with their corresponding sources [given by (16) and (27), respectively]. However, as we will discuss in the next two subsections, *in practice* there are some technical obstacles to overcome first.

### A. Sources: Even-parity sector

As we have defined it, the second-order Zerilli function  ${}^{(2)}\Psi$ , and in consequence also the source of the equation it obeys,  ${}^{(2)}S_\Psi$ , diverges at large radii. In order to see this, it is sufficient to take its gauge-invariant definition (11) and (12), assume an asymptotically flat gauge, and impose conditions (49)–(55) and (65)–(67). In this way, we find that the quadratic source  ${}^{(2)}Q_\Psi$  diverges as

$${}^{(2)}Q_\Psi = Q_2 r^2 + Q_1 r + Q_0 + \mathcal{O}\left(\frac{1}{r}\right), \quad (74)$$

where  $Q_0$ ,  $Q_1$ , and  $Q_2$  are quadratic functions of  $\{\hat{F}, \bar{F}, \hat{J}, \bar{J}\}$ . The hat and bar on  $F$  and  $J$  denote the generic harmonic labels  $(\hat{l}, \hat{m})$  and  $(\bar{l}, \bar{m})$  of two first-order modes, respectively. For instance, the dominant term is given by

$$Q_2 = \sum_{\hat{l}, \hat{m}} \sum_{\bar{l}, \bar{m}} \frac{32}{\lambda \bar{l}^2 (\bar{l}+1)^2 \hat{l}^2 (\hat{l}+1)^2} E_{0\hat{l}\hat{m}}^{0\bar{l}\bar{m}} \ddot{\hat{F}} \ddot{\bar{F}}, \quad (75)$$

where the  $E$  coefficients, defined in Appendix A, are normalized products of two Clebsch-Gordan factors. In this case, the  $E$  coefficient restricts the sums to those harmonic labels  $\{\hat{l}, \bar{l}, l\}$ , such that  $\hat{l} + \bar{l} + l$  is an even number. That is, for the cases in which  $\hat{l} + \bar{l} + l$  is an odd number the term  $Q_2$  cancels out. In contrast, the term  $Q_1$  has a nonvanishing contribution in all cases.

These divergences are nonphysical, and have their origin in the freedom to add low-order gauge-invariant terms in the definition of the second- and higher-order Zerilli functions, as discussed in Sec. III. Fortunately, they can be removed by exploiting that freedom to regularize the source of the Zerilli equation. In that way  ${}^{(n)}\Psi$  will obey the same equation but with a different, nondiverging source term. The following discussion is rather technical, but necessary. The reader not interested in the details, though, might skip it and refer to Eq. (87) [and (92) for the odd-parity sector], keeping in mind that we have made use of the freedom in defining the second-order master functions



in such a way that their associated sources are nondivergent both at the horizon and at infinity.

Our aim is to obtain some quadratic terms on the first-order Zerilli functions and GS master scalars  $Q_{\text{reg}} = Q_{\text{reg}}[\{\hat{\Psi}, \bar{\Psi}, \hat{\Pi}, \bar{\Pi}\}]$ , which reproduce the asymptotic divergent behavior of the source  $Q_{\Psi}$  near null infinity. That is, for  $r \gg M$  with  $u = \text{const}$ ,

$$\begin{aligned} Q_{\text{reg}}[\{\hat{\Psi}, \bar{\Psi}, \hat{\Pi}, \bar{\Pi}\}] &= Q_2[\{\hat{F}, \bar{F}, \hat{J}, \bar{J}\}]r^2 \\ &+ Q_1[\{\hat{F}, \bar{F}, \hat{J}, \bar{J}\}]r \\ &+ Q_0[\{\hat{F}, \bar{F}, \hat{J}, \bar{J}\}] + \mathcal{O}\left(\frac{1}{r}\right). \end{aligned} \quad (76)$$

In order to construct the function  $Q_{\text{reg}}$  we make the following replacements in  $Q_2$ ,  $Q_1$ , and  $Q_0$ :

$$\dot{F} \rightarrow \frac{1}{2}l(l+1)\Psi, \quad \ddot{J} \rightarrow \frac{r^3}{2}l(l+1)\Pi. \quad (77)$$

These rules include all cases but the first and zeroth derivatives. There are no  $F$  or  $J$  terms without derivatives in the divergent terms, but there are some first-order derivatives. Hence, the straightforward definition would be

$$\dot{F} \rightarrow -r^2 \left( \frac{\partial \Psi}{\partial r} \right)_u. \quad (78)$$

However, these replacements introduce divergences at the horizon  $r = 2M$ . In order to see this, we choose ingoing Eddington-Finkelstein coordinates, which are smooth at the horizon. They are obtained from the Schwarzschild coordinates  $(t, r)$  by the following transformation:

$$t \rightarrow w \equiv t + 2M \ln \left| \frac{r}{2M} - 1 \right|. \quad (79)$$

In these coordinates the two-dimensional background metric takes the form

$$\begin{aligned} g_{AB}dx^A dx^B &= -\left(1 - \frac{2M}{r}\right)dw^2 + \frac{4M}{r}dw dr \\ &+ \left(1 + \frac{2M}{r}\right)dr^2. \end{aligned} \quad (80)$$

Therefore, we have the following relation between coordinate derivatives:

$$\left( \frac{\partial \Psi}{\partial r} \right)_u = \left( \frac{\partial \Psi}{\partial r} \right)_w + \frac{r + 2M}{r - 2M} \left( \frac{\partial \Psi}{\partial w} \right)_r, \quad (81)$$

which makes explicit the divergence of the radial derivative in outgoing coordinates at the horizon  $r = 2M$ . Taking into account Eq. (78) this implies that the source diverges there as well.

In order to regularize the source at large radii without introducing divergences at the horizon we proceed in the following way: First, we make a Taylor expansion in inverse powers of  $r$  of the right-hand side of Eq. (81). Next, we define a derivative that approaches  $(\partial/\partial r)_u$  for

large  $r$ , but without being divergent at the horizon. Following this method we get

$$\dot{F} = -r^2 \left( \frac{\partial \Psi}{\partial r} \right)_w - (r^2 + 4Mr + 8M^2) \left( \frac{\partial \Psi}{\partial w} \right)_r + \mathcal{O}\left(\frac{1}{r}\right), \quad (82)$$

which is finite at the horizon. Converting this last relation into Schwarzschild coordinates gives the following rules to reconstruct the divergent terms:

$$\dot{F} \rightarrow -r^2 \Psi' + \frac{r^3 - 16M^3}{2M - r} \dot{\Psi}, \quad (83)$$

$$\ddot{J} \rightarrow -r^2 (r^3 \Pi)' + \frac{r^3 - 16M^3}{2M - r} r^3 \dot{\Pi}. \quad (84)$$

The replacements (77) and (83) must be done systematically. That is, first take  $Q_2 r^2$  and reconstruct the term that will reproduce it,

$$\sum_{\hat{l}, \hat{m}} \sum_{\bar{l}, \bar{m}} \frac{8r^2}{\lambda \bar{l}(\bar{l}+1) \hat{l}(\hat{l}+1)} E_{0\hat{l}\hat{m}}^{0\bar{l}\bar{m}} \ddot{\Psi} \dot{\bar{\Psi}}. \quad (85)$$

When expanding near null infinity, this term will go as  $Q_2 r^2 + R_1 r + R_0 + \mathcal{O}(r^{-1})$ . In order to remove the divergent terms of order  $\mathcal{O}(r)$ , it is not enough to find a term that will reproduce  $Q_1 r$ , it must reproduce  $(Q_1 - R_1)r$ , to compensate the new term we have just introduced. Therefore, we take  $(Q_1 - R_1)r$  and make the above replacements (77) and (83) again. And so on, until we achieve the desired quadratic function  $Q_{\text{reg}}[\{\hat{\Psi}, \bar{\Psi}, \hat{\Pi}, \bar{\Pi}\}]$ , which asymptotically behaves as in Eq. (76).

In this way, we define the regularized second-order Zerilli function as

$$\{2\}\Psi_{\text{reg}} \equiv \{2\}\Psi + Q_{\text{reg}}. \quad (86)$$

It obeys the following wave equation:

$$\{2\}\Psi_{\text{reg}l}{}^m|_A - V_Z \{2\}\Psi_{\text{reg}l}{}^m = \{2\}\mathcal{S}_{\Psi}^{\text{reg}}, \quad (87)$$

where the regularized source is given by

$$\{2\}\mathcal{S}_{\Psi}^{\text{reg}} \equiv \{2\}\mathcal{S}_{\Psi} + Q_{\text{reg}l}{}^m|_A - V_Z Q_{\text{reg}}. \quad (88)$$

We have implemented this regularization procedure for generic  $(l \geq 2)$  first- and second-order modes, but the results are quite lengthy. Just to illustrate the point, though, we explicitly show the final result for the regularization factor for the particular case  $(\hat{l}, \hat{m}) = (\bar{l}, \bar{m}) = (l, m) = (2, 0)$ :

$$\begin{aligned}
Q_{\text{reg}} = & -\frac{1}{252(2M-r)}\sqrt{\frac{5}{\pi}}[2(2M-r) \\
& \times [(9M+r)\{^1\dot{\Psi} + 6\{^1\Psi\}^{\{1\}}\dot{\Psi} \\
& + (110M^3 - 21rM^2 + 14r^2M + 4r^3)\{^1\dot{\Psi}\}^{\{1\}}\ddot{\Psi} \\
& - 2(2M-r)[4r^2\{^1\Psi'\} - (15M-6r)\{^1\Psi\}^{\{1\}}\ddot{\Psi}] \\
& - \frac{3r^6}{224}\sqrt{\frac{5}{\pi}}\{16\{^1\dot{\Pi}\}^{\{1\}}\ddot{\Pi} + (2r-3M)\{^1\dot{\Pi}\}^{\{1\}}\ddot{\Pi}\}.
\end{aligned} \tag{89}$$

### B. Sources: Odd-parity sector

In the axial case there is no such divergence. Following the same steps as above, one finds that near null infinity the quadratic part of the RW function  $^{(2)}\Phi$  tends to

$$^{(2)}Q_{\Phi} = Q_{\Phi}^{(0)} + \mathcal{O}\left(\frac{1}{r}\right). \tag{90}$$

Therefore, in principle there is no need to regularize the second-order RW function. But, as it will be clear in the next subsection, we are still interested in removing the term of order  $\mathcal{O}(1)$ . We do so by applying the same procedure as in the polar case, namely, we obtain a term  $Q_{\Phi}^{\text{reg}}$ , which reproduces  $Q_{\Phi}^{(0)}$  at null infinity.

After that we define the regularized second-order RW variable as

$$^{(2)}\Phi_{\text{reg}} \equiv ^{(2)}\Phi + Q_{\Phi}^{\text{reg}}, \tag{91}$$

$$\begin{aligned}
\text{Power} = & \frac{\varepsilon^2}{64\pi r^2} \sum_{l,m} \frac{(l+2)!}{(l-2)!} \left\{ r^4 \left| \frac{\partial^{\{1\}} G_l^{mAF}}{\partial t} \right|^2 + \left| \frac{\partial^{\{1\}} h_l^{mAF}}{\partial t} \right|^2 + \varepsilon \text{Re} \left[ r^4 \frac{\partial^{\{1\}} G_l^{mAF}}{\partial t} \left( \frac{\partial^{\{2\}} G_l^{mAF}}{\partial t} \right)^* + \frac{\partial^{\{1\}} h_l^{mAF}}{\partial t} \left( \frac{\partial^{\{2\}} h_l^{mAF}}{\partial t} \right)^* \right] \right\} \\
& + \mathcal{O}(\varepsilon^4),
\end{aligned} \tag{95}$$

where Re means the real part. Again, the problem of finding the radiated power reduces to calculating the harmonic coefficients  $G_l^m$  and  $h_l^m$  near null infinity, in an asymptotically flat gauge. More precisely, we want to relate them with the regularized master scalars constructed in the previous two subsections.

In those subsections we regularized the second-order master variables so that the quadratic contributions from first-order modes decay as  $\mathcal{O}(1/r)$  near null infinity. Hence, we can use their gauge-invariant definitions, (12) and (18), and assume an AF gauge (29)–(32) up to second order. This leads to the very same relations as at first-order; namely,

$$^{(2)}G_l^{mAF} = \frac{2\{^2\}\Psi_{l\text{reg}}^m}{l(l+1)r} + \mathcal{O}\left(\frac{1}{r^2}\right), \tag{96}$$

$$^{(2)}h_l^{mAF} = 2r\{^2\}\Phi_{l\text{reg}}^m + \mathcal{O}(r^0). \tag{97}$$

Replacing these expressions in Eq. (95), the radiated power up to order  $\varepsilon^3$  is given in terms of the master scalars by

$$\begin{aligned}
\text{Power} = & \frac{\varepsilon^2}{64\pi} \sum_{l,m} \frac{(l+2)!}{(l-2)!} \left\{ \frac{4}{l^2(l+1)^2} \left| \frac{\partial^{\{1\}} \Psi_l^m}{\partial t} \right|^2 + \frac{r^6}{\lambda^2} \left| \frac{\partial^{\{1\}} \Pi_l^m}{\partial t} \right|^2 \right. \\
& \left. + \varepsilon \text{Re} \left[ \frac{4}{l^2(l+1)^2} \frac{\partial^{\{1\}} \Psi_l^m}{\partial t} \left( \frac{\partial^{\{2\}} \Psi_{l\text{reg}}^m}{\partial t} \right)^* - \frac{2r^3}{\lambda} \frac{\partial^{\{1\}} \Pi_l^m}{\partial t} \{^2\}\Phi_{l\text{reg}}^{m*} \right] \right\} + \mathcal{O}(\varepsilon^4).
\end{aligned} \tag{98}$$

and its evolution equation

$$^{(2)}\Phi_{\text{reg}l}{}^m{}_{|A} - V_{\text{RW}}{}^{(2)}\Phi_{\text{reg}l}{}^m = ^{(2)}\mathcal{S}_{\Phi}^{\text{reg}}, \tag{92}$$

where the regularized source is again given by

$$^{(2)}\mathcal{S}_{\Phi}^{\text{reg}} \equiv ^{(2)}\mathcal{S}_{\Phi} + Q_{\Phi}^{\text{reg}}{}_{|A}{}^{A} - V_{\text{RW}} Q_{\Phi}^{\text{reg}}. \tag{93}$$

As in the even-parity case, we shall not present the details of the general procedure but instead simply explicitly show the final result for the regularization factor for the  $(\hat{l}, \hat{m}) = (\bar{l}, \bar{m}) = (l, m) = (2, 0)$  case:

$$Q_{\Phi}^{\text{reg}} = -\frac{r^3}{84}\sqrt{\frac{5}{\pi}}\{3\ddot{\Pi}\dot{\Psi} + \ddot{\Pi}\Psi + \ddot{\Psi}\Pi\}. \tag{94}$$

The regularized sources for the equations of motion (87) and (92) are one of the main results of this article. We have calculated them for the presence of any first- and second-order axial or polar modes. We do not include their explicit form here because they are quite lengthy and do not contribute to the discussion. They are available from the authors upon request. As an illustration, for the interested reader, in Appendix B we have written down their explicit form for some particular values of the harmonic labels.

### C. Radiated power

Once we have solved for the first and second-order master equations we can obtain the radiated power by using Eq. (37). Expanding it explicitly up to order  $\varepsilon^3$ , it takes the following form:

This last formula, complemented with the evolution equations for the regularized master scalars constructed above, provides a closed set of formulas that permits to obtain the radiated power up to order  $\varepsilon^3$  in the most general case in a fully consistent way.

At this point we want to discuss an aspect of second-order perturbations of Schwarzschild black holes, which seems not to have been discussed before in the literature. Namely, even when we are solving for the metric up to second-order perturbations, we can only obtain the *complete* radiated power up to third order in  $\varepsilon$ . In order to obtain the following order  $\varepsilon^4$ , one should also consider third-order perturbations.

Let us further elaborate on this point. Consider the simplest possible scenario: a unique first-order mode with harmonic labels  $(l, m)$  and polarity  $\sigma$ . The polarity  $\sigma$  will take the value 1 for even-parity/polar modes and  $-1$  for odd-parity/axial modes. Because of reality conditions, if the mode  $(l, m, \sigma)$  is present, so is its conjugate  $(l, -m, \sigma)$ .

The self-coupling of this mode will generate several second-order modes but not in general the one with labels  $(l, \pm m, \sigma)$ . In contrast, at third order the mode with indices  $(l, \pm m, \sigma)$  will indeed be generated. This means that the

third-order modes will always contribute to the emitted power at order  $\varepsilon^4$ , coupled to the first-order mode with the same harmonic labels. Therefore, without considering third-order modes, one can only obtain the radiated power consistently up to order  $\varepsilon^3$ .

In order for the emitted power (37) to have a contribution of that order ( $\varepsilon^3$ ) the self-coupling of the first-order mode must give a second-order mode with the same labels  $(l, m, \sigma)$ . It is easy to see that, when only considering a first-order mode  $(l, \pm m, \sigma)$ , this will happen if and only if  $m = 0$  and if, for  $\sigma = 1$  ( $\sigma = -1$ ),  $l$  is an even (odd) number.

In order to make the above discussion more explicit and analyze which problems can be addressed consistently, let us consider the particular case of a first-order even-parity/polar mode with harmonic labels  $l = m = 2$  and  $l = m = -2$ . These modes will generate the second-order  $\{l = 4, m = \pm 4, 0\}$ ,  $\{l = 2, m = 0\}$ , and  $\{l = 0, m = 0\}$  even-parity/polar modes as well as the  $\{l = 3, m = 0\}$  odd-parity/axial mode. Particularizing the power formula (37) in terms of the master scalars to this case, we obtain the following contributions from the modes:

$$\text{Power} = \frac{\varepsilon^2}{12\pi} |\partial_t \Psi_2^{\{1\}}|^2 + \frac{9\varepsilon^4}{640\pi} \{|\partial_t \Psi_4^{\{2\}}|^2 + 2|\partial_t \Psi_4^{\{2\}}|^2\} + \frac{15\varepsilon^4}{8\pi} |\Phi_3^{\{2\}}|^2 + \frac{\varepsilon^4}{96\pi} |\partial_t \Psi_2^{\{2\}}|^2, \quad (99)$$

where the second-order master scalars are the regularized ones. Here, it can be clearly seen that the order  $\varepsilon^3$  is not present. The problem with this last formula is that it is not complete since the third-order  $\{l = 2, m = \pm 2\}$  polar mode would contribute to the power at order  $\varepsilon^4$ .

On the other hand, let us consider the first-order mode  $l = 2$  with all its possible harmonic labels  $m = 0, \pm 1, \pm 2$ . By coupling, they will generate the second-order polar modes  $l = 0, l = 2$ , and  $l = 4$  with all their possible  $m$ . That is, we will have the second-order  $\{l = 0, m = 0\}$ ,  $\{l = 2, m = 0, \pm 1, \pm 2\}$ , and  $\{l = 4, m = 0, \pm 1, \pm 2, \pm 3, \pm 4\}$  polar modes. This particular case will provide a nonvanishing  $\varepsilon^3$ -order term to the power,

$$\begin{aligned} \text{Power} = & \frac{\varepsilon^2}{24\pi} \{2|\partial_t \Psi_2^{\{1\}}|^2 + 2|\partial_t \Psi_2^{\{1\}}|^2 + |\partial_t \Psi_2^{\{1\}}|^2\} \\ & + \frac{\varepsilon^3}{24\pi} \text{Re}[2\partial_t \Psi_2^{\{1\}} \partial_t \Psi_2^{\{2\}*} + 2\partial_t \Psi_2^{\{1\}} \partial_t \Psi_2^{\{2\}*} + \partial_t \Psi_2^{\{1\}} \partial_t \Psi_2^{\{2\}*}] + \mathcal{O}(\varepsilon^4), \end{aligned} \quad (100)$$

where, again, the second-order Zerilli function must be understood as regularized. In this last case the formula is exact up to the displayed order, to which the generated second-order axial modes and third-order polar modes do not contribute.

## VII. FINAL REMARKS

In this paper we have introduced a complete gauge-invariant formalism to study arbitrary perturbations of a Schwarzschild black hole up to second order. In particular, we regularized the resulting equations, making them suitable for a numerical implementation.

This formalism enables a variety of applications and studies. These range from the nonlinear stability of the black hole horizon, to nonlinear features in gravitational waves and mode-mode coupling. We will report those studies elsewhere.

All calculations of this paper have been done with and have been largely possible at all due to new, efficient symbolic manipulation tools. The resulting expressions in most cases are very long and their explicit forms are not particularly enlightening. For that reason we have refrained from explicitly presenting most of them. They are however, available upon request.

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## APPENDIX A: TENSOR SPHERICAL HARMONICS

Tensor fields of any rank  $s$  on the sphere will be decomposed using a basis of tensor spherical harmonics. Such a basis can be constructed from the symmetric trace-free (STF) tensors

$$Z_l^m{}_{a_1 \dots a_s} \equiv (Y_l^m : a_1 \dots a_s)^{\text{STF}}, \quad (\text{A1})$$

$$X_l^m{}_{a_1 \dots a_s} \equiv \epsilon_{(a_1}{}^b Z_l^m{}_{b a_2 \dots a_s)}, \quad (\text{A2})$$

together with the metric  $\gamma_{ab}$  and the antisymmetric tensor  $\epsilon_{ab}$  [2]. For the particular case  $s = 0$ , those objects must be read as  $Z_l^m \equiv Y_l^m$  and  $X_l^m \equiv 0$ . They are normalized in the following way:

$$\int d\Omega Z_l^m{}_{ab} \gamma^{ac} \gamma^{bd} (Z_{l'}^{m'}{}_{cd})^* = \frac{1}{2} \frac{(l+2)!}{(l-2)!} \delta_{ll'} \delta_{mm'}, \quad (\text{A3})$$

$$\int d\Omega X_l^m{}_{ab} \gamma^{ac} \gamma^{bd} (X_{l'}^{m'}{}_{cd})^* = \frac{1}{2} \frac{(l+2)!}{(l-2)!} \delta_{ll'} \delta_{mm'}, \quad (\text{A4})$$

$$\int d\Omega X_l^m{}_{ab} \gamma^{ac} \gamma^{bd} (Z_{l'}^{m'}{}_{cd})^* = 0. \quad (\text{A5})$$

Going beyond linear perturbation theory, the nonlinear coupling between two first-order modes results in products between two tensor spherical harmonics  $(l, m, s)$  and  $(l', m', s')$ . Those products can be decomposed into a linear combination of harmonics  $(l'', m + m', s + s')$  with an explicit formula involving coefficients

$$E_{s'l'm'l''}^{slm} \equiv \frac{k(l', l, s') k(l, l, s)}{k(l'', l, s + s')} C_{l' l''}^{m' m m' + m} C_{l' l''}^{s' s s' + s}, \quad (\text{A6})$$

where  $C_{l' l''}^{m' m m' + m}$  are the usual Clebsch-Gordan coefficients and  $k$  is a normalization factor defined by

$$k(l, s) = \sqrt{\frac{(2l+1)(l+s)!}{2^{s+2} \pi (l-s)!}}. \quad (\text{A7})$$

These  $E$  coefficients encode the geometric selection rules that determine which pairs of modes do actually couple. See [2] for full details.

## APPENDIX B: REGULARIZED SOURCES, SOME EXPLICIT EXAMPLES

In this appendix we show two particular examples for the regularized sources of the RW (92) and Zerilli Eqs. (87).

Let us first assume that we have the first-order  $\{l = 2, m = 1\}$  even-parity/polar and  $\{l = 8, m = -4\}$  odd-parity/axial modes. The regularized source generated by them for the equation of motion of the, for example, second-order  $\{l = 7, m = 3\}$  even-parity/polar mode is given by

$$\begin{aligned} S_{\Psi}^{\text{reg}} = & -\frac{i\sqrt{\frac{22}{51\pi}}r}{945(U+9)^2(2U-1)(3U+2)^2} \{ -60\Pi_{,tr}(6U^3 + 55U^2 + 7U - 18)^2 r^3 \Psi_{,rr} \\ & + 60\Pi_{,rr}(6U^3 + 55U^2 + 7U - 18)^2 r^3 \Psi_{,tr} - 20\Pi_{,tr}(U+9)^2(18U^4 + 51U^3 - 58U^2 - 26U + 20) r^2 \Psi_{,r} \\ & - 5\Pi_{,t}(3U+2)^2(212U^4 + 3364U^3 + 11603U^2 - 13149U + 3240) r^2 \Psi_{,rr} + 20\Pi_{,rr}(U+9)^2(126U^4 + 141U^3 \\ & - 82U^2 - 50U + 20) r^2 \Psi_{,t} + 5\Pi_{,r}(3U+2)^2(308U^4 + 4972U^3 + 17255U^2 - 22221U + 6156) r^2 \Psi_{,tr} - 180\Pi_{,tr} \\ & \times (U+9)^2(6U^4 + 9U^3 + 2U^2 + 4U - 4) r \Psi + \Pi_{,t}(360U^6 + 2568U^5 + 57529U^4 - 14036U^3 \\ & + 375894U^2 + 88254U - 123444) r \Psi_{,r} + \Pi_{,r}(14220U^6 + 253302U^5 + 1234181U^4 + 854111U^3 - 966354U^2 \\ & - 375354U + 220644) r \Psi_{,t} + 15\Pi(3U+2)^2(92U^4 + 1492U^3 + 8507U^2 + 14154U - 9396) r \Psi_{,tr} \\ & - \Pi_{,t}(6840U^6 + 112128U^5 + 422069U^4 + 1424U^3 - 213006U^2 + 271944U - 48924) \Psi \\ & + \Pi(6210U^6 + 116313U^5 + 1283789U^4 + 6929894U^3 + 6649074U^2 - 316926U - 1359504) \Psi_{,t} \}, \end{aligned} \quad (\text{B1})$$

where  $U \equiv M/r$ .

As a second example, we show the regularized source for the RW Eq. (92) for the particular case in which the first-order even-parity/polar modes  $(\bar{l} = 3, \bar{m} = 0)$  and  $(\hat{l} = 4, \hat{m} = -1)$  generate a second-order odd-parity/axial mode with labels  $(l = 4, m = -1)$ :



$$\begin{aligned}
S_{\Phi}^{\text{reg}} = & \frac{3i}{8800\sqrt{7}\pi(U+3)^4(2U-1)^2(3U+5)^4} \left\{ -10r(3U^2+14U+15)^4 \hat{\Psi}_{,rrr} \bar{\Psi}_{,rr} (2U-1)^5 \right. \\
& + 26r(3U^2+14U+15)^4 \hat{\Psi}_{,rr} \bar{\Psi}_{,rrr} (2U-1)^5 - \frac{(3U+5)^2}{r^2} (3060U^8 + 49401U^7 + 332356U^6 + 1197973U^5 \\
& + 2636572U^4 + 3760905U^3 + 2764530U^2 - 467775U - 1518750) \hat{\Psi}_{,rr} \bar{\Psi} (2U-1)^3 \\
& + \frac{(U+3)^2}{r^2} (1620U^8 + 28161U^7 + 173844U^6 + 197637U^5 - 1511900U^4 - 5534775U^3 - 7023550U^2 \\
& - 3510375U - 573750) \hat{\Psi} \bar{\Psi}_{,rr} (2U-1)^3 + 10r(3U^2+14U+15)^4 \hat{\Psi}_{,trr} \bar{\Psi}_{,tr} (2U-1)^3 \\
& - 26r(3U^2+14U+15)^4 \hat{\Psi}_{,tr} \bar{\Psi}_{,trr} (2U-1)^3 - \frac{16(1-2U)^2}{r^4} (1701U^{11} + 35262U^{10} + 320166U^9 + 1720086U^8 \\
& + 6285736U^7 + 16821825U^6 + 34748135U^5 + 56990175U^4 + 68601150U^3 + 42931125U^2 - 5703750U \\
& - 15946875) \hat{\Psi} \bar{\Psi} - \frac{2}{r^3} (6U^2+7U-5)^2 (1530U^9 + 34221U^8 + 303099U^7 + 1485635U^6 + 4592169U^5 \\
& + 9179205U^4 + 10353033U^3 + 3316365U^2 - 2994975U - 1478250) \hat{\Psi}_{,r} \bar{\Psi} \\
& - \frac{10}{r} (U+3)^2 (6U^2+7U-5)^4 (U^3+9U^2+27U+90) \hat{\Psi}_{,rrr} \bar{\Psi} + \frac{2}{r^3} (2U^2+5U-3)^2 (24138U^9 + 399357U^8 \\
& + 2535795U^7 + 8866263U^6 + 20189321U^5 + 31979265U^4 + 34936825U^3 + 20024625U^2 - 4674375U \\
& - 9618750) \hat{\Psi} \bar{\Psi}_{,r} + \frac{8}{r^2} (6U^3+25U^2+16U-15)^2 (90U^7 + 468U^6 + 1763U^5 + 5632U^4 + 22704U^3 \\
& - 6480U^2 - 35025U + 15750) \hat{\Psi}_{,r} \bar{\Psi}_{,r} + \frac{2}{r} (U+3)^2 (6U^2+7U-5)^3 (675U^5 + 5741U^4 + 15946U^3 \\
& + 24570U^2 + 10590U - 13950) \hat{\Psi}_{,rr} \bar{\Psi}_{,r} - 5(U+3)^3 (11U-9) (6U^2+7U-5)^4 \hat{\Psi}_{,rrr} \bar{\Psi}_{,r} \\
& - \frac{2}{r} (3U+5)^2 (2U^2+5U-3)^3 (1377U^5 + 11403U^4 + 25994U^3 + 19250U^2 - 410U - 10350) \hat{\Psi}_{,r} \bar{\Psi}_{,rr} \\
& - 8(1-2U)^4 (3U^2+14U+15)^3 (30U^3 + 91U^2 + 99U + 15) \hat{\Psi}_{,rr} \bar{\Psi}_{,rr} + \frac{78}{r} (3U+5)^2 (2U^2+5U-3)^4 \\
& \times (3U^3 + 15U^2 + 25U + 50) \hat{\Psi} \bar{\Psi}_{,rrr} + 13(3U+5)^3 (17U-15) (2U^2+5U-3)^4 \hat{\Psi}_{,r} \bar{\Psi}_{,rrr} \\
& - \frac{8}{r^2} (3U^2+14U+15)^2 (198U^7 + 1164U^6 + 2627U^5 + 17137U^4 + 45972U^3 + 3140U^2 - 38100U + 11475) \\
& \times \hat{\Psi}_{,t} \bar{\Psi}_{,t} - \frac{2}{r} (U+3)^2 (3U+5)^3 (474U^6 + 4575U^5 + 13106U^4 + 20156U^3 + 1014U^2 \\
& - 23685U + 8100) \hat{\Psi}_{,tr} \bar{\Psi}_{,t} + 5(1-2U)^2 (U+3)^3 (3U+5)^4 (4U^2+23U-9) \hat{\Psi}_{,trr} \bar{\Psi}_{,t} \\
& + \frac{2}{r} (U+3)^3 (3U+5)^2 (2142U^6 + 13005U^5 + 21826U^4 + 13968U^3 - 4370U^2 - 21115U + 8100) \\
& \times \hat{\Psi}_{,t} \bar{\Psi}_{,tr} + 24(U^2-3U-5) (6U^3+25U^2+16U-15)^3 \hat{\Psi}_{,tr} \bar{\Psi}_{,tr} \\
& \left. - 13(1-2U)^2 (U+3)^4 (3U+5)^3 (12U^2+37U-15) \hat{\Psi}_{,t} \bar{\Psi}_{,trr} \right\}. \tag{B2}
\end{aligned}$$

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